Bursts of ULF noise excited by sudden changes of solar wind dynamic pressure

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Abstract. We present the results of analysis of the dayside magnetic pulsation response to a sudden change in solar wind dynamic pressure. We concentrate on the events when a burst or a series of short-lived bursts in the Pc1 frequency range with the repetition period of 7–15 min were observed on the ground around the local noon. Not every impulse of large amplitude caused this phenomenon. We have found that the ULF bursts were excited when the spectrograms of the DMSP satellites showed a signature of 10–30 keV ions in the vicinity of the magnetic flux tube of the ground observatory, that may be related to a geomagnetic storm preceding the event. In light of this finding a possible model of the phenomenon is suggested in which the hot protons influence significantly both the generation and modulation of Pc1 activity.

Key words. Magnetospheric physics (solar wind – magnetosphere interaction; MHD waves and instabilities; storms and substorms)

1 Introduction

There is a class of geomagnetic pulsations in the Pc1 frequency range ($f = 0.1 - 5$ Hz) for which one can identity the cause of their appearance. They are the pulsations observed on the ground during the compression of the magnetosphere by a sudden change of solar wind dynamic pressure (sudden impulse, SI). These pulsations are often referred to as "SI-excited micropulsations". Olson and Lee (1983) have shown that the increase in the temperature anisotropy of the magnetospheric plasma arising from the sudden compression of the geomagnetic field is one of the primary causes of the wave activity observed after SIs. Thus, the SI-excited micropulsations, when studied, can provide insight into the internal structure of the magnetosphere.

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In accordance with the classification scheme suggested by Kangas et al. (1986), the SI-excited micropulsations may be divided into three categories:

- Pc1 events, typically "hydromagnetic chorus" emissions which start within a few minutes of the SI;
- short-lived bursts of ULF emissions;
- cases where Pc1 pulsations are delayed by more than 30 min.

It is also known that the SI causes an increase in the carrier frequency of the preceding "pearl-type" activity (Troitskaya et al., 1968; Olson and Lee, 1983). The pulsations of second category pointed out by Kangas et al. (1986) as the most interesting events are the subject of this investigation.

The statistical study of the SI-excited short-lived bursts in the ULF noise was started by Tepley and Wentworth (1962). Their results indicated that only 20% of SIs are accompanied by a single burst at middle latitudes and that most of them occurred near the noon meridian. Similar results were obtained later by Kangas et al. (1986) for the auroral zone. They also found that the probability of burst excitation depended on the SI's amplitude and that during the 30 or 40 min just after an SI, one might see fainter bursts following the first one.

In the present study we concentrate on SI-induced micropulsations having the form of a sequence of bursts (SB) centered near $f = 1$ Hz. We will examine both the amplitude of SI and the state of the magnetosphere during SI to understand why only some of them caused the ULF response on the ground. We will do this by analysing the WIND satellite data on solar wind dynamic pressure and the DMSP data on hot protons in the magnetosphere.

The paper is organized as follows. In Sect. 2 we describe briefly the instrumentation used. In Sect. 3 we present the morphological features of SBs. In Sect. 4 we examine the hot proton fluxes measured by the DMSP satellite, examining which particles seem to be associated SBs. In Sect. 5 the phenomenon is discussed in light of preceding geomagnetic

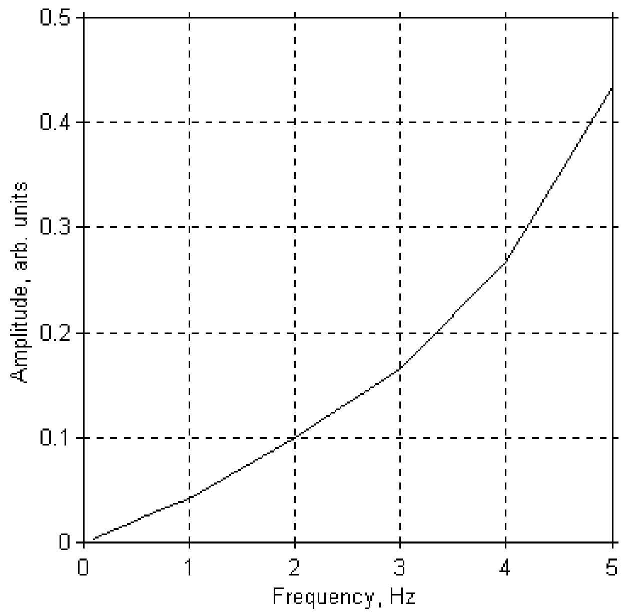

Fig. 1. The amplitude-frequency response of the induction magnetometer in LOZ.

activity. In Sect. 6 we summarize the results and discuss the possible scenario of SB generation. Section 7 is a brief conclusion.

2 Instrumentations

The key instrument used in this study was the automatic magnetic station (two-component induction magnetometer) installed at the observatory Lovozero, LOZ, (67.97° N; 35.02° E; MLT = UT + 2.6 h). The high resolution magnetic data from the Sodankyla geophysical observatory, SOD, (67.37° N; 26.63° E; MLT = UT + 2.1 h), which is located approximately 500 km west of LOZ, were also analyzed for comparison.

The LOZ induction magnetometer operated at the sampling rate of 40 Hz, which allowed for the registration of magnetic pulsations in a frequency band from 0.1 to 20 Hz. Since the data used were not corrected for the frequency response, we present the amplitude-frequency characteristic of the magnetometer in Fig. 1. The vertical scale in Fig. 1 corresponds to the magnetometer's output amplitude in response to a constant-amplitude sinusoidal input signal of varying frequency. To construct the sonogram showing the development of a pulsation spectrum in time, the power spectra of the magnetic signal were calculated for the intervals of ∼25 s in duration (1024 samples) taken with an ∼20 s overlap. This yielded not more than a 20 s error in definition of pulsation enhancement in a sonogram. The digital records of the data at SOD were produced with the sampling rate of 20 Hz.

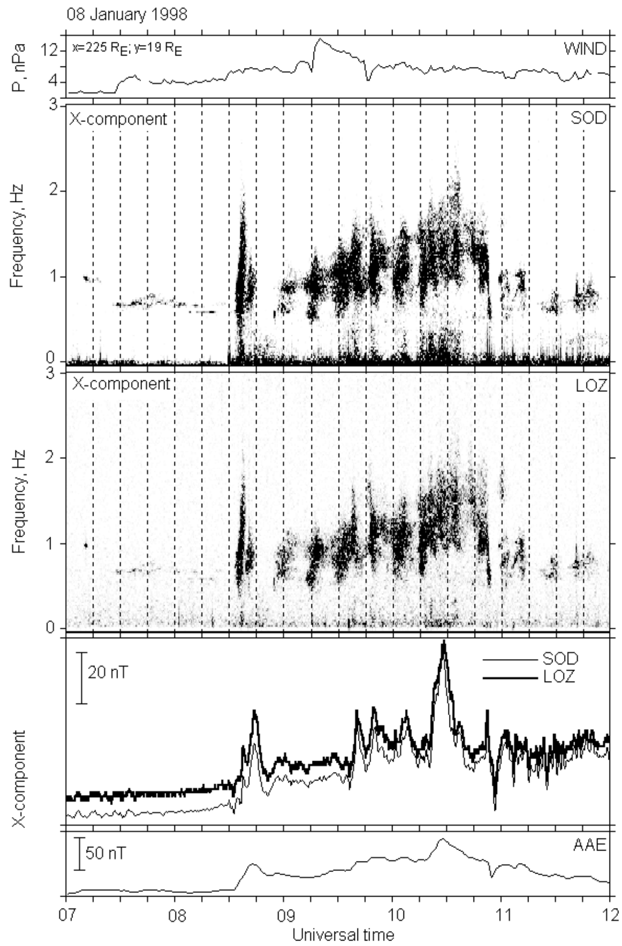

Fig. 2. An example of series of ULF bursts excited by a sudden change in solar wind dynamic pressure. From top to bottom: the solar wind pressure variations at the WIND satellite, sonograms from two magnetic stations (Lovozero and Sodankyla), variation of the geomagnetic field in the auroral zone and at the equatorial station Addis Ababa.

3 Results of observations

3.1 A case study: SI excited bursts on 8 January 1998

An example of the ULF response to sudden impulse is presented in Fig. 2. Variations of solar wind dynamic pressure measured by the WIND satellite are shown in the top panel. There were three sudden impulses which occurred at about 07:30 UT, 08:30 UT and 09:15 UT. All SIs caused a step-like increase in the magnetic X-component at the equatorial station Addis Ababa, AAE, (9.02° N; 38.77° E; MLT = UT + 2.3 h), shown in the bottom panel. The amplitudes of SIs in space and on the ground were 4.0 nPa, 1.8 nPa, 7.2 nPa, and 40 nT, 20 nT, 30 nT, respectively. The velocity of the solar wind was 350 km/s; thus, the one hour delay between the SI in the WIND and AAE data corresponds to the propagation time of the solar wind discontinuity to the magnetopause.

The sonograms in Fig. 2 show the SI-induced pulsation activity. Both observatories were near the noon meridian at

Table 1. Characteristics of sudden impulses and accompanying ULF activity in Pc1 frequency range

No.	Date		K_p	Δp,	ΔX,	N	T,	First burst		Particles	
	Day	Time UT		nPa	nT		min	f_m, Hz	$\Delta f/\Delta t$, Hz/min	MLAT degs	Time, UT (satellite)
1	2	3	4	5	6	7	8	9	10	11	12
1	24.10.97	11:15	4	5.5	40	1	–	0.8	$\propto$	–	–
2	24.11.97	07:25	2	2.8	15	>10	15	0.7	uncl	66.5	07:35 (F12)
										68.6	08:56 (F14)
										67.0	09:17 (F12)
3	08.01.98	08:35	2	4.0	40	5	15	1.0	0.33	–	data gap
4		09:40	3	1.8	20	4	15	1.2	$\propto$	63.0	09:50 (F14)
5		10:20	3	7.2	30	7	uncl	uncl	uncl	–	–
6	01.02.98	09:05	3	3.2	25	1	–	0.8	0.15	–	–
7	18.02.98	08:19	4	1.0	7	3	12	1.0	uncl	65.0	08:38 (F12)
8		08:45	4	3.5	35	6	12	1.1	$\propto$	–	–
9	30.04.98	09:35	3	6.5	60	1	–	1.3	0.50	68.5	10:15 (F14)
10	03.05.98	07:45	5	12	130	2	5	1.5	$\propto$	68.4	07:54 (F14)
11	26.06.98	10:20	4	10.5	35	2	15	2.6	0.60	–	–
12	26.08.98	06:50	5	6.5	100	1	–	1.3	−0.25	–	–
13	02.10.98	07:25	5	5.2	80	3	15	1.6	0.45	66.0	07:53 (F12)
14	07.11.98	08:20	3	2.5	35	>20	10	1	$\propto$	66.0	08:55 (F12)
15	21.04.99	07:00	3	2.0	5	1	–	1.1	$\propto$	–	–
16		07:30	3	3.2	40	4	10	1.3	$\propto$	–	–
17	22.09.99	12:20	5	8.8	40	1	–	1.0	$\propto$	–	–
18		12:30	5	7.2	10	7	7	1.7	0.25	–	–
19	26.11.00	08:00	4	10.5	40	7	10	1.7	1.25	–	no data
20	23.01.01	10:50	4	5.5	30	>10	10	1.3	2.0	–	no data

that time. It is seen that every SI was accompanied by a series of short-lived bursts, with the center frequency near 1 Hz. The number of bursts is more than 10. The period of the burst sequence (repetition period) is about 15 min and does not vary significantly during the interval. The duration of the event is 2.5 h. The form of activity in the LOZ sonogram is very close to that in SOD. The onsets of bursts in LOZ and SOD also coincide.

The pulsation activity following the SI with a form of a single burst or sequence of bursts (SB) is the subject of this study.

3.2 Statistical features of the SI-excited bursts of the ULF noise

We have analyzed the solar wind ion pressure data through the periods from June 1997 to January 2000 and from November 2000 to February 2001. Sometimes the WIND trajectory passed far away from the Earth (near 200 R_E). To define correctly the moment of magnetospheric compression, we also examined the data from magnetic equatorial stations Addis Ababa, Alibag (ABG, 18.63° N; 72.87° E; MLT = UT + 4.5 h) and Lunping (LNP, 25.00° N; 121.17° E; MLT = UT + 7.7 h). Altogether, 196 events were analysed. Only 20 SB events were found to follow the SI. (We do not consider here other forms of the ULF response.) Some characteristics of those events are presented in Table 1. In the second and third columns we indicate the start times of the events in the sonogram. The K_p index for the 3 h interval, including the moment of SI is in the fourth column. The SI amplitude in space and on the ground is presented in the fifth and sixth columns, respectively. The next two columns contain the information about the number of bursts in the series and the repetition period. In the ninth column the center frequency of the first burst is given. The frequency rate, defined in the next section, is indicated in the tenth column. Some characteristics of DMSP flights above the Scandinavian and Kola peninsulas are presented in the two last columns and will be discussed in more detail in Sect. 4.

3.2.1 Signal dispersion

For some events, the bursts in the sonogram look like narrow bands of rising or falling frequency. We illustrate this in Fig. 3 where an SB event with the first burst is shown (some more examples of dispersive bursts can be found in Fig. 8). The ULF activity on the ground was initiated by a sudden impulse with the intensity of 5 nPa. The solar wind velocity was ∼700 km/s, so the delay of SI in a AAE magnetogram in Fig. 3a corresponds to the propagation of the front of irregularity from the WIND satellite to the Earth.

The dynamic spectrum of the first burst is presented in

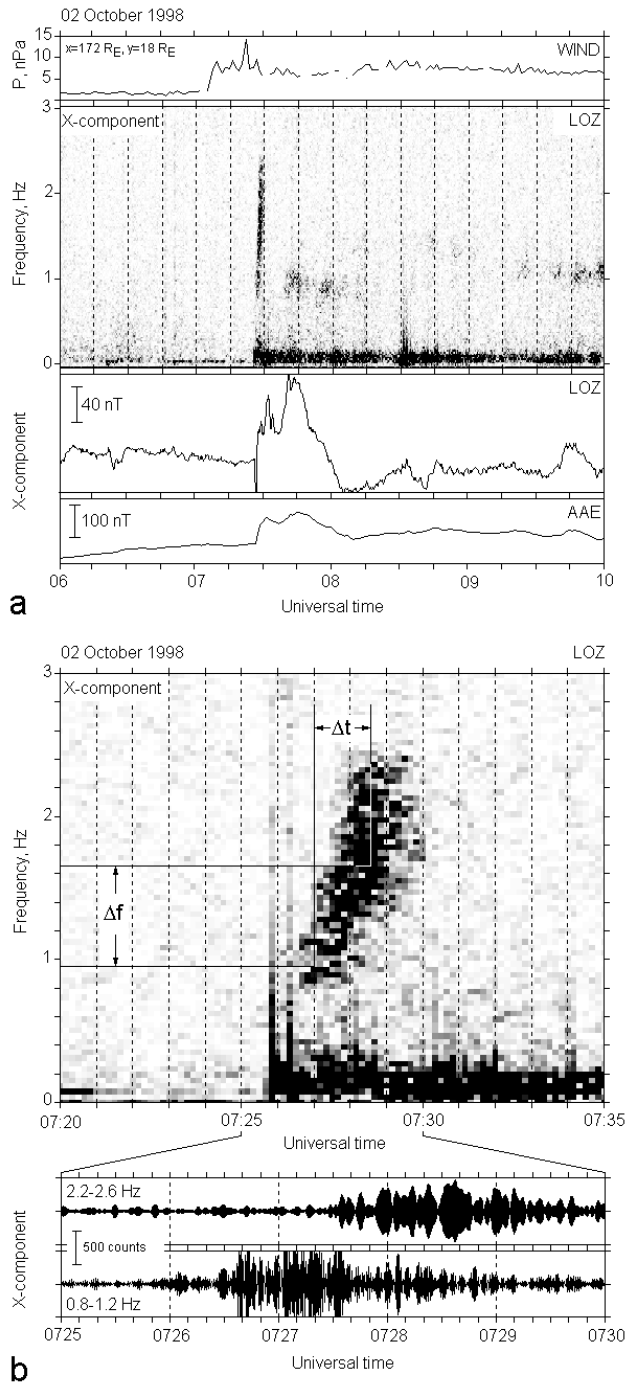

Fig. 3. An example of SB event with the first burst manifested. **(a)** The same as in Fig. 1. **(b)** The dispersive characteristics of the first burst (top) and the result of signal filtering in two frequency bands (bottom).

Fig. 3b with a higher resolution. The frequency of the signal increases by $\Delta f = 0.7$ Hz during $\Delta t = 90$ s. Approximately the same value of Δt is obtained by the comparison of two filtered signals in Fig.3b (bottom). The amplitude of the signal in the band of 0.8–1.2 Hz is $1.5 \cdot 10^{-2}$ nT, and it decreases to the value of $0.5 \cdot 10^{-2}$ nT for the signal filtered in the band of 2.2–2.6 Hz.

It was difficult to define the dispersion of all bursts due to a rather complex form of ULF activity (for instance, the signal superposition which occurred after 10:00 UT in Fig. 2). For this reason we have estimated the frequency rate, calculated as $\Delta f / \Delta t$, for the first burst only. Here Δf is the difference between the maximum and the minimum frequencies of a raising tone, and Δt is its duration (see also Fig. 3). The results are presented in Table 1 in the ninth column. Here the sign "–" means that the frequency is decreasing, the symbol "uncl" corresponds to the cases of unclear dispersion. In some cases the value of Δt was less than Δt accuracy (40 s, as was mentioned above). Those events are indicated by the symbol "$\propto$". It is seen from Table 1 that for most of the first bursts the frequency increases in time. In Fig. 4 we present an example of the superposition of the SB event with the preceding activity of the "pearl" type. The SI caused the increase in the carrier frequency of the pearls. Note that the frequency of the burst increases faster than the frequency of a single pearl as well as the carrier frequency.

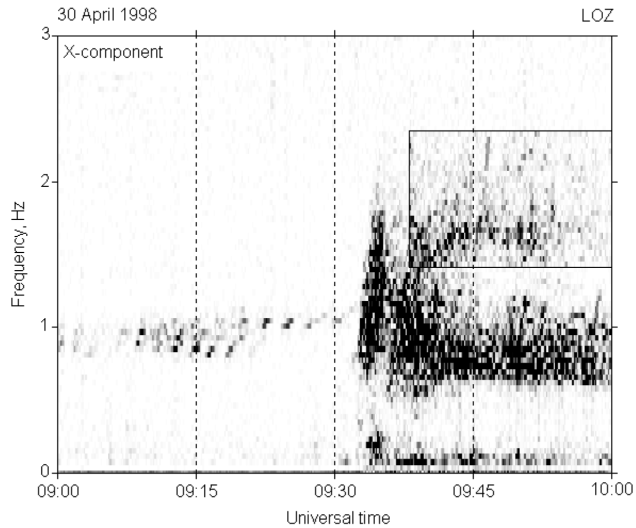

Fig. 4. Excitation of the ULF burst and the increase of the "pearls" carrier frequency during the magnetosphere copmpression.

3.2.2 MLT distribution and relation to SI amplitude

We have analyzed 180 positive and 16 negative sudden impulses of different intensity. No negative SI (i.e. sudden decrease in solar wind dynamic pressure) caused the SB event on the ground, whereas the probability of observing the SB after positive SI was ~10%. For convenience, we shall use a term "YES events" to denote the sudden impulses with SB. In contrast, the SIs which were not accompanied by the ULF activity will be referred to as "NO events".

All "YES events" were detected in LOZ and SOD in the local time interval between 09:00 and 16:00 MLT (see Fig. 5a). In this MLT sector only 74 SIs occurred, and the probability of "YES event" is about 27%, with maximum near 10:00 MLT. There is also dawn-to-dusk asymmetry in the MLT-distribution with a much more abrupt decrease to the morning sector.

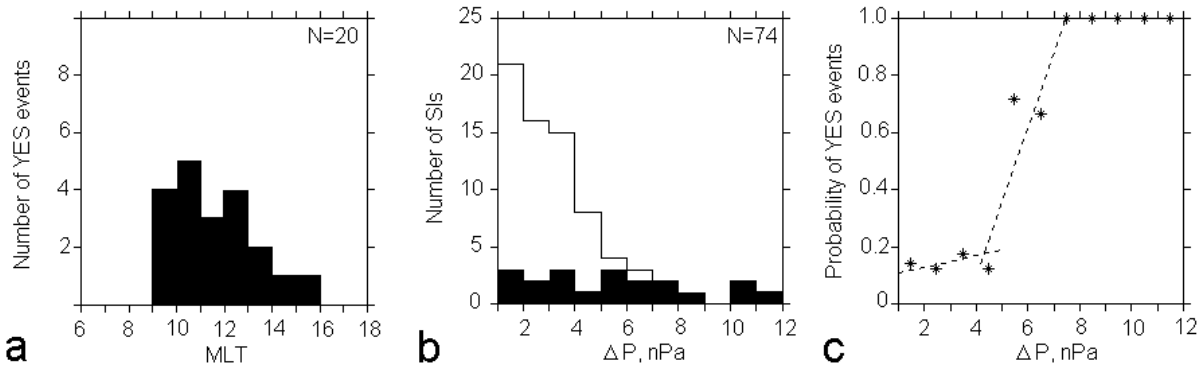

Fig. 5. **(a)** MLT distribution of "YES events". **(b)** Number of SIs versus the SI intensity (SIs with ULF bursts after them are indicated with black). **(c)** Probability of "YES events" as a function of SI intensity.

In the Figs. 5b and c we present the probability of the SB occurrence as a function of SI amplitude. The diagram in Fig. 5b shows the occurrence of both all SIs and "YES events" (the latter are indicated as black squares). Note that the number of SIs decreases with the SI amplitude. For example, only 4 SIs have the amplitude $>$ 8 nPa for the SIs of this investigation, which is 13 times less than the number of SIs between 1 and 4 nPa. For this reason, the probability of "YES events" in Fig. 5c increases with the SI intensity.

3.2.3 Relation to variations of plasma pressure in the solar wind and long-period magnetic pulsations on the ground

Approximately half of the SB events under consideration lasted for more than 2 h and demonstrated a good periodicity. Namely, the ULF bursts recurred with a period of 10–15 min. We compared these events with solar wind data and concluded that only a small number of the ULF bursts in the series seems to be connected with ion pressure variations in the solar wind. In particular, it is seen in Fig. 2 and in two other cases, which are presented in Figs. 6 and 9 and will be discussed later in connection with DMSP observations. Note that the first burst for the events in Figs. 2 and 4 is more intense than for the events in Figs. 6 and 9 when the solar wind pressure increased more slowly.

The variations of the geomagnetic field at the nearby auroral zone station and at the equatorial station are shown below each sonogram. As in the case of the solar wind pressure, there is no "peak-to-peak" correlation between the long-period magnetic pulsations on the ground and the ULF bursts.

4 Observations of hot protons in the dayside magnetosphere during SI

In this section we present the results which we obtained from the analysis of DMSP spectrograms when the satellite was above the Scandinavian and Kola peninsulas.

4.1 The difference between "YES events" and "NO events" in hot proton data

The main result obtained may be formulated as follows. During the "YES events", the spectrograms show signatures of precipitating protons with energy more than 10 keV. During "NO events", the precipitating particles are absent. This difference is illustrated in Fig. 6. We have chosen for comparison two SIs which occurred approximately at the same local time and had amplitudes of 2.5 nPa and 3.5 nPa. The SI in Fig. 6a is a typical "YES event" as it is accompanied by the sequence of the ULF bursts. Some numerical characteristics of this SI and accompanying ULF activity are shown in Table 1. In contrast, there was no ULF activity after a rather intense SI presented in Fig. 6b. We classified this SI as a "NO event".

Open arrows in the spectrograms indicate the moments of DMSP F12 flight above Scandinavia. The appropriate fragments of F12 trajectories are mapped in Fig. 6c. The trajectory corresponding to the "YES event" is emphasized with a bold line. The spectrograms along the trajectories are presented in Fig. 7. The spectrogram (a) is obtained during a "YES event" and spectrogram (b) corresponds to a "NO event". During the "YES event", the satellite observed hot ($>$10 keV) protons near 08:55:16 UT. In spectrogram (a) these protons are shown as a dark area between 67° and 66° MLAT. In Fig. 6c the ionospheric projection of this area is shown with a black square. There are no precipitating protons along the satellite trajectory during the "NO event" (in spectrogram b).

There were 9 "YES events" when DMSP was above Scandinavia. The precipitating protons with energy $>$10 keV were detected during all of these events. The position of the equatorial boundary of the precipitation region and the moment of observation of hot protons are given in Table 1 in the two last columns. We have also examined 8 "NO events". The dates of their occurence are listed in Table 2 (second and third columns). The K_p index for the 3 h interval, including the moment of SI, is in the fourth column. The SI ampli-

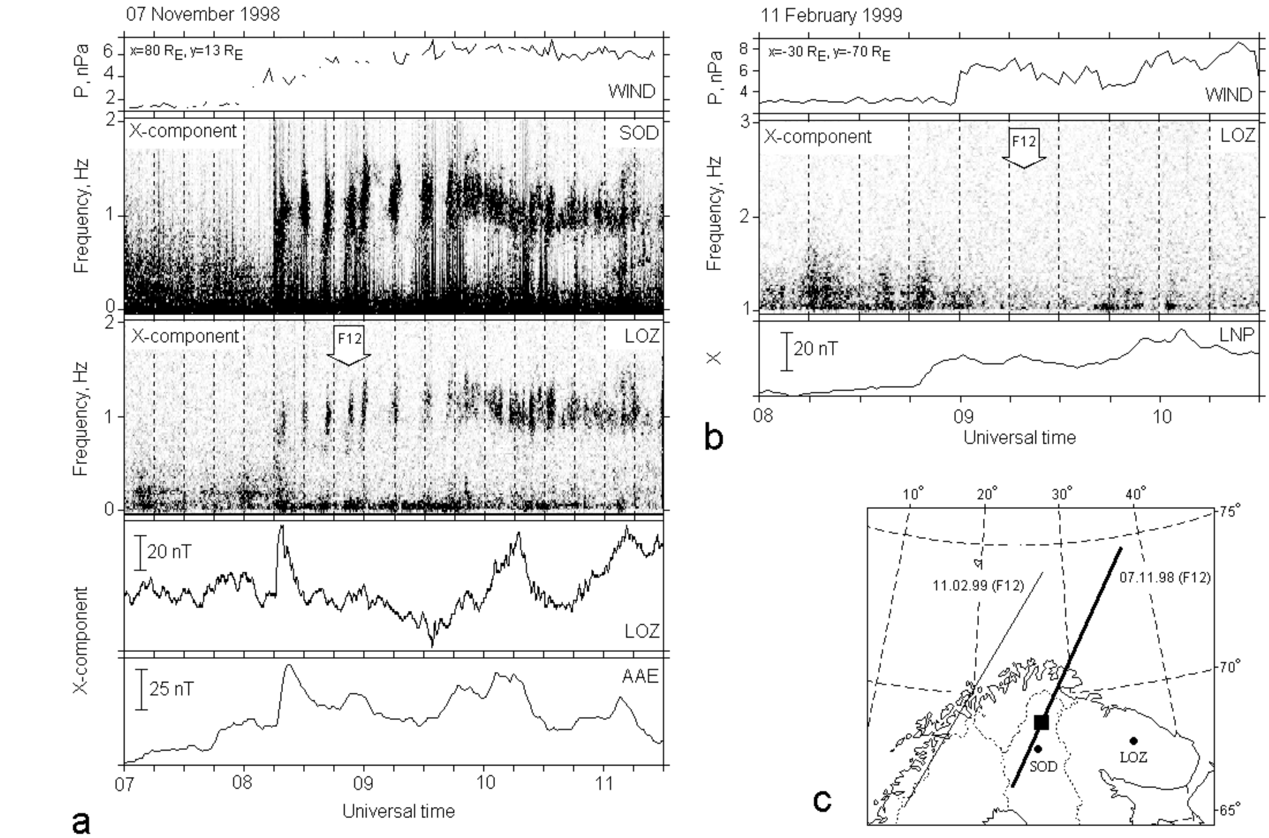

Fig. 6. Examples of two SIs accompanied **(a)** and not accompanied **(b)** by the SB-events. Also shown is the map **(c)** with trajectories of DMSP F12 for the moments indicated with open arrows on dynamic spectra **(a)** and **(b)**.

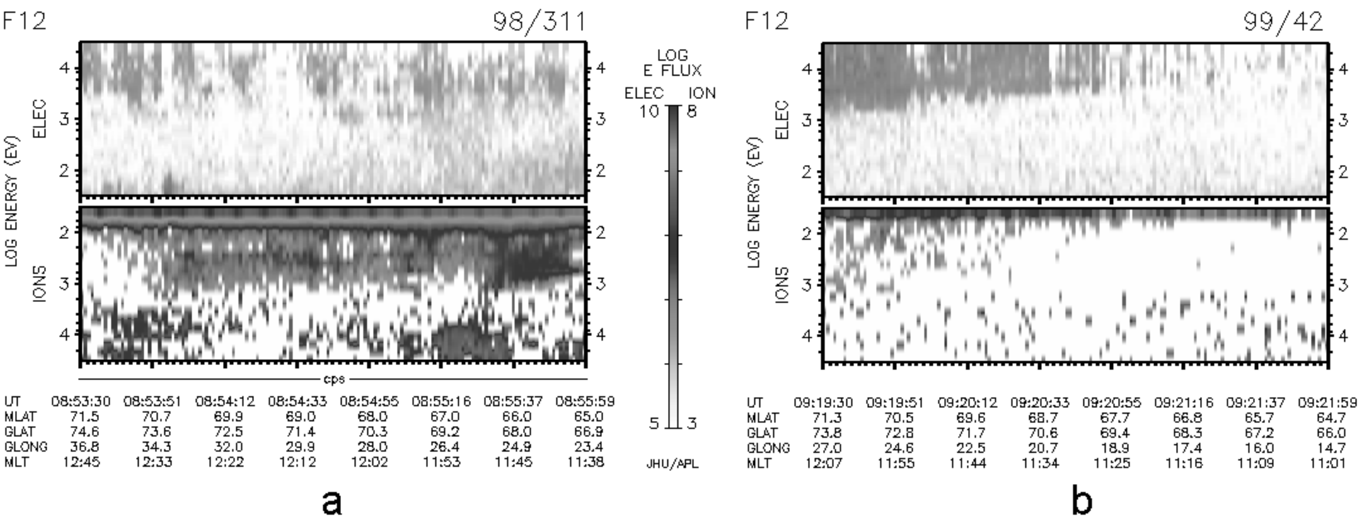

Fig. 7. Comparison of two spectrograms of DMSP F12 for the events **(a)** and **(b)** in Fig. 6.

tudes in space and on the ground are indicated in the fifth and sixth columns, respectively. The last column contains a flight time of the satellite above the Scandinavian or Kola peninsulas. It is important that DMSP did not detect any hot protons in the dayside magnetosphere below 70° MLAT during these events.

4.2 Features of precipitating region

The spatial/temporal ambiguity appears every time when interpreting the satellite data. Our data shows that the hot protons were observed independently from the burst, namely sometimes the satellite detected the protons before the ULF

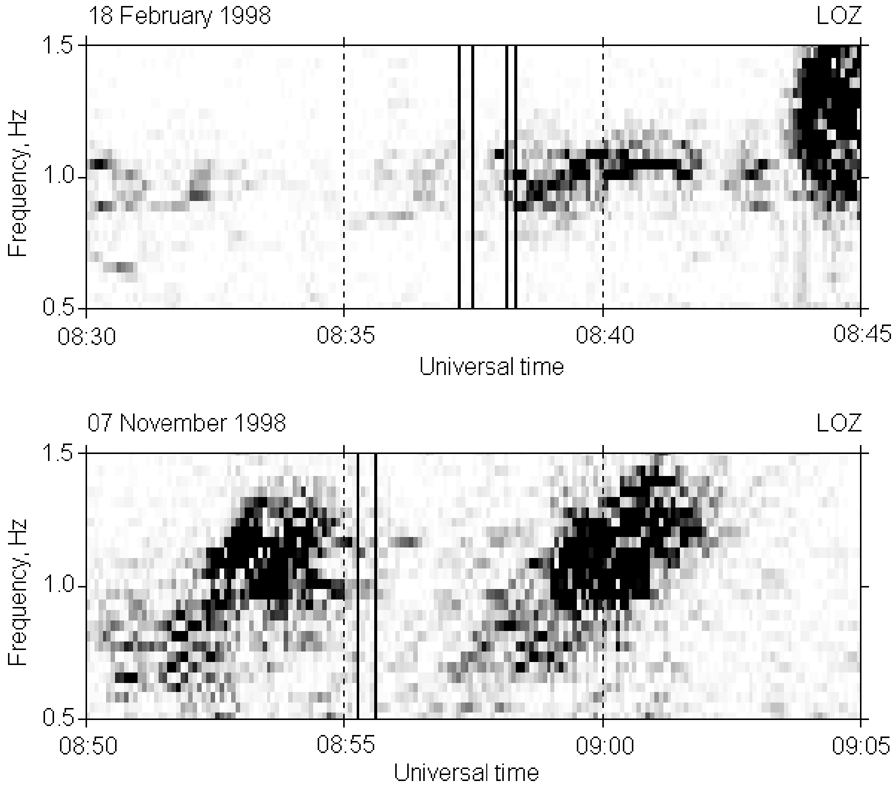

Fig. 8. Excitation of the ULF burst in relation to the moment of observation of hot protons (the interval of proton precipitation is marked with two vertical lines).

burst enhancement, and sometimes the precipitation followed the ULF burst. There were also events when the burst and the particles were seen simultaneously. Two examples of observation of the hot protons before and after the burst are presented in Fig. 8. The vertical bold lines in the sonograms indicate the interval of observation of >10 keV protons from the satellite. The precipitating protons are seen for ∼30 s (note that it is less than the burst duration). So, we think that the observed precipitations are a spatial rather than a temporal feature, and satellite detected them when passed through the precipitating region. The width of this region in the ionosphere is about 1° MLAT (∼100 km), which corresponds to ∼0.8 R_E in the magnetosphere (R_E is the Earth's radius).

For all "YES events" with proton precipitation mentioned above, the satellite's trajectories passed in the vicinity of the midday meridian. Below we discuss a case on 24 November 1997 when the data from two satellites were available and one of them passed the high latitudes from dusk to dawn. This event is described in Fig. 9. The gradual compression of the magnetosphere resulted in the ULF activity in the form of SB (see sonogram in Fig. 9a). In Fig. 9b we present the spectrograms from F12 and F13 satellites obtained along the fragments of trajectories shown on the MLT-MLAT diagram in the right bottom corner. The precipitating protons are seen in the midday and evening sectors, but are not detected in the morning. The absence of hot protons at dawn was also found during "YES events" 2 and 14 (see Table 1). During those events, the satellite F13 flew almost along the magnetic meridian and crossed the auroral zone twice: first in the dusk (near 07:40 UT on 24 November 1997 and near 09:20 UT on 7 November 1998) and a few minutes later in the dawn – and detected the hot protons in the dusk only. So, the precipitating protons are observed mostly in the noon; there are a few examples when they are also seen in the dusk but we have found no precipitation in the morning. This MLT-distribution of precipitating protons during "YES events" is the third result of the present study.

Table 2. List of the sudden impulses which have not excited ULF activity to be observed on the ground

N	Data	Time UT	K_p	Δp, nPa	ΔX, nT	Flight time, UT (satellite)
1	2	3	4	5	6	7
1	23.10.97	08:05	2	1.5	20	08:45–08:49 (F14)
2	31.03.98	07:30	3	1.5	20	07:59–08:01 (F14)
3	08.05.98	08:00	3	1.0	25	08:34–08:37 (F14)
4		09:52	4	3.0	60	10:16–10:19 (F14)
5	03.08.98	10:45	2	2.5	15	10:47–10:51 (F14)
6	16.12.98	07:30	3	2.5	25	07:58–08:02 (F14)
7	11.02.99	08:50	3	3.5	15	09:20–09:23 (F12)
8	22.11.99	09:50	4	2.0	15	10:35–10:39 (F14)

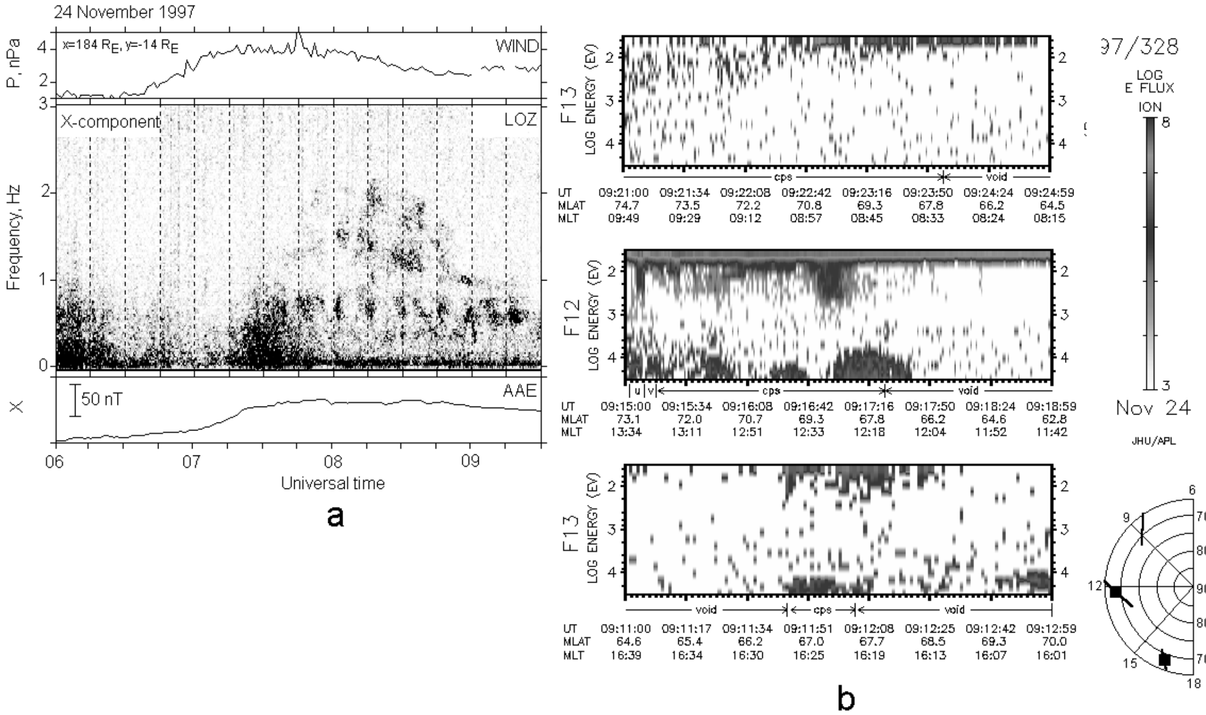

Fig. 9. Hot protons in the dayside magnetosphere during the "YES event". **(a)** Variations of dynamic pressure on the WIND satellite (top panel), corresponding increase of geomagnetic field at equatorial station (bottom panel) and ULF response in dayside auroral zone (middle panel). **(b)** DMSP particles data in the dawn, midday and dusk sectors of magnetosphere. The precipitating areas are indicated in the diagram (right bottom) with black squares.

5 Relation to K_p and D_{st} indexes

It is known that some type of Pc1 pulsations correlates with the global geomagnetic activity estimated by the K_p index (Kangas et al., 1998). Our data demonstrate such a tendency as well. As one can infer from the tables, that K_p reaches 5 for some of the "YES events", whereas the "NO events" correspond to the $K_p < 4$. But it is necessary to note that the mean values of K_p do not differ significantly ($K_p \approx 3$ and $K_p \approx 3.5$ for "NO" and "YES" events, respectively).

In accordance with the statistical model based on DMSP data (Hardy et al., 1989), the precipitating protons with energies >10 keV are observed between 65 and 70 MLAT around noon when the K_p index is large (K_p = 5 in the paper cited). For the low and moderate activity (K_p = 1 and K_p = 3), the average energies of protons in this MLAT-MLT sector do not exceed 10 keV. In principle, this is also consistent with our results. In fact, some "YES events" occurred during very disturbed intervals (K_p = 5), whereas for "NO events" the K_p varied from 2 to 4. But it is again necessary to note, that the mean value of K_p is 3 for the "NO events" and is 3.2 for those "YES events", when hot protons in the DMSP data were observed.

A more distinct difference in geomagnetic conditions for "YES" and "NO" events may be found if one compares the D_{st} variations for the two days preceding the event. In Fig. 10 the day of the event is indicated as the day "0". It is seen that the intervals on the left, on average, have more negative changes in D_{st} before the times when the SBs were excited. One can also see that those negative changes have the form typical for magnetic storms. So, we conclude that the sequence of bursts, as well as the hot protons shown in the DMSP spectrograms, occurred at the end of the recovery phase of the weak or moderate magnetic storms (except for the event on 30 April 1998, when the ULF response had the form of a single burst). In contrast, the SIs, which occurred under quiet magnetic conditions, did not initiate the ULF activity.

In our study the precipitating protons were detected inside the ionospheric projection of the central plasma sheet (indicated as *cps* on the spectrograms in Figs. 7 and 9) and should be of the inner magnetospheric origin. We think that they are the low-altitude signature of hot protons injected into the dayside magnetosphere from the magnetotail during the magnetic storm. These protons were reported earlier by Borovsky et al. (1998) as a "superdense ion plasma sheet" appearing around the Earth during the magnetic storm. Since the appearance of hot protons on the DMSP spectrograms does not coincide in time with the ULF burst (see Sect. 4.2), we think that the interaction with cold plasma of the plasmaspheric origin rather than the magnetospheric compression is the reason for their precipitation. Such plasma is often observed in the afternoon-dusk sector after magnetic storms (Carpenter et al., 1993).

6 Summary and discussion

The principal findings of the investigation of ULF burst-like responses to sudden changes in the solar wind dynamic pressure based on the data covering more than 2 years are the following:

1. About 10% of the positive SIs were accompanied by ULF activity in the form of a single burst or a series of bursts (SB) with a center frequency near 1 Hz. The first burst in the series was the most intense, with the exception of cases when the solar wind pressure increased slowly. In most cases the frequency of the first burst increased at the mean rate of 0.75 Hz/min.

2. Repetition period of the bursts did not vary significantly during the series, but may be different for different events (7–15 min). Some SB events lasted for 3 h. There is no peak-to-peak correlation between bursts in a series and variations in plasma pressure in the solar wind, as well as long period magnetic pulsations on the ground.

3. SBs were observed near local noon.

4. There is no significant dependence of the SB occurrence on SI amplitude. But the probability of the SB excitation seems to be large for large SI.

5. In half of the “YES events”, the DMSP trajectories passed above Scandinavian and Kola peninsulas. During these passes the satellites detected precipitating protons with energy >10 keV near the midday meridian at geomagnetic latitudes below 70°. There are a few cases when the hot protons were also seen in the dusk part of trajectory but none were observed in the morning sector. During “NO events”, hot protons were not observed in the midday magnetosphere.

6. The precipitating protons do not seem to be due to the wave-particle interaction, since they were seen independently from the burst enhancement.

7. Almost all of the “YES events” mentioned in 5 occurred at the end of the recovery phase of the weak or moderate magnetic storms.

The most comprehensive study of SI-excited ULF bursts was made by Tepley and Wentworth (1962) and Kangas et al. (1986). But they did not concentrate on the series of bursts and did not compare them with satellite data. One SB event with the repetition period of 5 min in the magnetosphere was reported by Rasinkangas et al. (1994). Recently, Engebretson (2001) reported two types of pulsations in the 0.1–0.4 frequency band generated in the compressed magnetosphere. Thus, the results listed above are new, except for points 3 and 4, which we present here to extend the published statistics of the phenomenon. We emphasize that points 5–7 are the most important results of our study and may promote an understanding of why it is the case that not all of the SIs

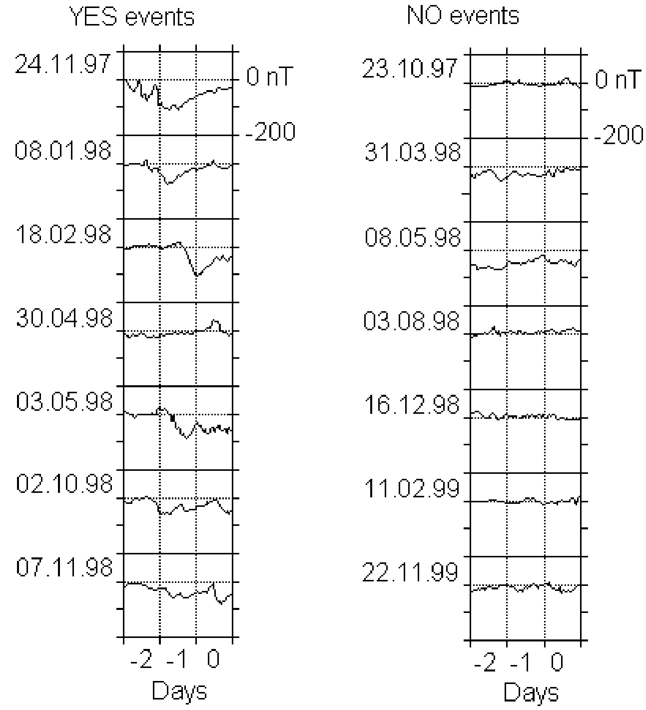

Fig. 10. Comparison of preceding geomagnetic activity for “YES events” and “NO events”. The day “0” means the day when SI response was examined.

resulted in the ULF activity on the ground and suggest the possible scenario of SB generation.

We think that the precipitating particles are the low-altitude signature of the hot protons in the magnetosphere. The proton distribution in the dayside magnetosphere was studied by many authors. In particular, Sergeev et al. (1997) reported a model based on NOAA low-altitude spacecraft data. Borovsky et al. (1998) used the data of geostationary satellites. The most comprehensive study of the DMSP data was made by Hardy et al. (1989), which resulted in the statistical model of ion distribution.

We interpret the absence of hot protons in the DMSP spectrograms (near noon during “NO events” and in the morning for ”YES events”) as the absence of hot plasma in the dayside magnetosphere. The gap of protons with energy >10 keV in the prenoon sector above 60° LAT was reported by Hardy et al. (1989), Liemohn et al. (2001) and it seems to be a spatial feature of distribution for both high and moderate levels of activity. In the midday magnetosphere, the presence of hot protons correlates in our data with magnetic storm activity.

The growth rate of the IC instability may be rewritten as

$$q \propto \Omega \cdot N_h \left(\frac{T_\perp}{T_{||}} \left(1 - \frac{\omega}{\Omega} \right) - 1 \right) \exp \left(- \left(\frac{\omega - \Omega}{B} \right)^2 \right), \quad (1)$$

where q is the local coefficient of amplification, ω is the wave frequency, Ω is the gyrofrequency of ions, $T_{||}$ and $T_\perp$ are the ion temperatures along and across the magnetic field, respectively, N_h is the concentration of hot ions, B is some coefficient (see Kangas et al., 1998). As hot protons contribute significantly to the IC instability growth rate, we assume that their absence is a possible reason of "NO events", as well as of non-observation of the ULF response in the morning sector.

It is seen from Eq. (1) that the amplification of the IC-wave is also defined by magnetic field compression (via gyrofrequency and anisotropy ratio, $T_\perp/T_{||}$). So, another reason for "NO events" may be the non-excitation of the long-period compressional wave causing the periodic growth of IC instability. There are two possible mechanisms of generation of this wave inside the magnetosphere-periodic variations of the solar wind plasma pressure and/or resonant oscillations of the magnetosphere. Since we do not find the corresponding variations in the solar wind (see Sect. 3.2.3), the latter mechanism seems to be more preferable for explaining the SB events. In the magnetospheric plasma, the compressional mode should be coupled with Alfvén mode. We think that this mixed wave is the wave that modulates the growth rate of the IC instability in the magnetosphere, as it was suggested by Rasinkangas et al. (1994) (see also Lyatsky and Plyasova-Bakunina, 1986; Anderson and Hamilton, 1993). For brevity we will use the term "modulating wave".

The global oscillations of the magnetosphere with a strong compressional component were discussed by many authors (Dungey, 1963; Kivelson et al., 1984; Denton and Vetoulis, 1998 and references therein). Most of the studies mentioned try to explain the compressional Pc 4–5 magnetic pulsations in the period range under 600 s. In our data the 15-min modulation of ULF activity is a typical case. Since no accompanying magnetic disturbances of the same periodicity are seen on the ground, these waves might be considered beyond the scope of studies in the past, although the larger periods might be obtained from Dungey's formula for estimation of the resonant period (Dungey, 1963):

$$T(c) \sim 0.6R_0^4, \tag{2}$$

where R_0 is the radial distance to the resonator wall taken in the R_E units. The substitution of the radial distance $\sim$6.2 R_E and 5.6 R_E to Eq. (2) gives $T\sim$15 minutes and $T\sim$10 min, respectively. It is interesting that this is close to a distance to the region of hot protons observed during the event on 7 November 1998 between $L = 6$ and $L = 5.5$ (in Tsyganenko, 1989 model).

A more detailed model of Kivelson et al. (1984) described the resonant oscillations of the magnetosphere during quiet magnetic conditions. In our case the SB events occurred under rather disturbed conditions and the presence of hot protons in the dayside magnetosphere should be taken into account. Perhaps the "superdense plasma sheet" (Borovsky et al., 1998) forms a cavity inside the magnetosphere, which may be a resonator for Dungey's oscillations. Note also that the model by Denton and Vetoulis (1998) supposes the generation of a poloidal mode in the presence of hot plasma enhancement between $L = 5.9$ and $L = 7.4$ with specific radial profile of plasma pressure. This spatial feature may also be formed due to storm-time injection.

In conclusion, the existence of hot protons in the dayside magnetosphere may play an important role both in the IC instability development and in the generation of the modulating wave.

The modulated phenomena without modulating wave signatures were reported earlier by Barfield et al. (1977) for periodical Pc1 activity and by Wright and Yeoman (1999) for the periodicity in the DOPE sounder data. The modulating wave may not exhibit simultaneous ground magnetic signature due to the following reasons. First, the modulating wave may be a high-m wave which cannot be resolved by ground magnetometer. Note that the compressional waves with a large azimuthal wave number are the waves generated in the above mentioned model by Denton and Vetoulis (1998). Second, although the wave has an Alfvén component, it does not reach the ionosphere. This may be due to a specific distribution of plasma along the magnetic field line (Safargaleev and Maltsev, 1986). The wave does not lose the energy in the ionosphere and exists for a long time without damping.

The first burst may be better manifested due to the contribution of the front of disturbance. We noted in Sect. 3.2.1 that $\Delta f/\Delta t$ for the burst differs from that for another well-known dispersive wave phenomenon called "pearl" pulsations. This may mean that different factors cause these phenomena. In accordance with Kangas et al. (1998), the frequency of IC wave may be estimated as

$$\omega < \left(1 - T_{||}/T_\perp\right)\Omega \tag{3}$$

and it increases if the anisotropy ratio, $T_{||}/T_\perp$, as well as the gyrofrequency of ions, Ω, increase during the magnetosphere compression. The model of Trakhtengerts et al. (2000) assumes constant anisotropy of energetic protons and suggests that the pearl frequency increases due to reflection properties of the ionosphere.

In conclusion, the fact that only a few SIs are accompanied by ULF activity on the ground may be easily understood in the frame of the following qualitative model. A sudden change in the solar wind dynamic pressure excites a magnetic disturbance with mixed Alfvén and compressional modes inside the magnetosphere. If the dayside magnetosphere is filled with hot (10–30 keV) protons, this disturbance has a form of the long-period oscillations. The compressional mode of the disturbance causes a periodic modulation of the ion-cyclotron instability of the magnetospheric plasma. The hot protons also contribute to the IC-instability growth rate. Since the modulating wave is the high-m wave, it is not detectable on the ground, and the phenomenon is manifested in ground magnetic data as a sequence of the ULF bursts having a central frequency around 1 Hz and a repetition period of the order of 7–15 min.

In general this model agrees with the suggestion by Anderson and Hamilton (1993) that for Pc1 generation the dayside magnetosphere should be near marginal stability for IC wave generation. In particular, it is expected that when the dayside magnetosphere is filled with hot protons, the recovery phase of the magnetic storm would be the most favourable condition for the IC wave generation (see Erlandson et al., 1994).

The possible reason of the midday maximum in the occurrence of SI-excited pulsations was discussed by Olson and Lee (1984) and Kangas et al. (1998). In our study, this maximum is shifted to the pre-midday sector (see Fig. 5a), which may be due to the geometry of the solar wind-magnetopause interaction. The observed dawn-to-dusk asymmetry may result from the MLT-distribution of precipitating protons mentioned in Sect. 4.2.

7 Conclusions

We have studied the morphological properties of the Pc1 frequency range geomagnetic pulsations, which are the ULF response to the sudden increase in solar wind dynamic pressure. Most of them have a form of a series of short-lived bursts (SB), with the frequency centred near 1 Hz and a repetition period of 7–15 min. It is found that such bursts take place in dayside auroral zone when a sufficient amount of hot (10–30 keV) protons is observed in the dayside magnetosphere, which occurred commonly during the recovery phase of magnetic storms. We suggest that these hot protons ("superdense" plasma sheet) create favourable conditions for the excitation of the long-period wave of mixed type with a strong compressional component. The periodic compression of the magnetic field results in the periodic enhancement of ULF noise on the ground through the modulation of the ion-cyclotron instability growth rate.

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References

Anderson, B. J. and Hamilton, D. C.: Electromagnetic ion cyclotron waves stimulated by modest magnetospheric compressions, J. Geophys. Res., 98, 11 369–11 382, 1993.

Barfield, J. N., Bondarenko, N., Buloshnikov, A., et al.: Synchronous observations of longperiod pulsations on the ATS-6 and at the surface of the Earth, Geomagnetism and Aeronomy, (Engl. Transl.), 17, 596–600, 1977.

Borovsky, J. E., Thomsen, M. F., McComas, D. J., et al.: Magnetospheric dynamics and mass flow during the November 1993 storm, J. Geophys. Res., 103, 26 373–26 394, 1998.

Carpenter, D. L., Giles, B. L, Chappell, C. R., et al.: Plasmasphere dynamics in the duskside bulge region: a new look at an old topic, J. Geophys. Res., 98, 19 243–19 272, 1993.

Denton, R. E. and Vetoulis, G.: Global poloidal mode, J. Geophys. Res., 103, 6729–6739, 1998.

Dungey, J. V.: The structure of the exosphere or adventures in velocity space, in: Deuitt, C. (Ed): Geophysics, The Earth's environment, Gordon and Breach, New York, 550, 1963.

Engebretson, M. J.: Observations of two types of compression-related unstructured PC 1–2 pulsations in the outer dayside magnetosphere, American Geophysical Union, Spring Meeting 2001, abstract no. SM61A-05, 2001.

Erlandson, R. E., Zanetti, L. J., Engebretson, M. J., et al.: Pc1 waves generated by a magnetospheric compression during recovery phase of a geomagnetic storm, in Solar wind sources of magnetospheric ultra-low-frequency waves, Geophysical Monograph 81, 399–408, 1994.

Hardy, D. A., Gussenhoven, M. S., and Brautigam, D.: A statistical model of auroral ion precipitation, J. Geophys. Res., 94, 370–392, 1989.

Kangas, J., Aikio, A., and Olson, J. V.: Multistation correlation of ULF pulsation spectra associated with sudden impulses, Planet. Space Sci., 34, 543–554, 1986.

Kangas, J., Guglielmi, A., and Pokhotelov, O.: Morphology and physics of short-period magnetic pulsations, Space Sci. Review, 83, 435–512, 1998.

Kivelson, M. G., Etcheto, J., and Trotignon, J. G.: Global compressional oscillations of the terrestrial magnetosphere: The evidence and a model, J. Geophys. Res., 89, 9851–9857, 1984.

Liemohn, M. W., Kozyra, J. U., Thomsen, M. F., et al.: Dominant role of the asymmetric ring current in producing the stormtime D_{st}, J. Geophys. Res., 106, 10 883–10 904, 2001.

Lyatsky, W. B. and Plyasova-Bakunina, T. A.: Influence of the Pc4 magnetic pulsations on Pc1 generation, Geomagnetism and Aeronomy, (Engl. Transl.), 26, 674–677, 1986.

Olson, J. V. and Lee, L. C.: Pc1 wave generation by sudden impulses, Planet. Space Sci., 31, 295–302, 1983.

Rasinkangas, R., Mursula, K., Kremser, G., et al.: Simultaneous occurrence of Pc5 and Pc1 pulsations in the dawnside magnetosphere: CRRES observation, in Solar wind sources of magnetospheric ultra-low-frequency waves, Geophysical Monograph 81, 417–424, 1994.

Safargaleev, V. V. and Maltsev, Yu. P.: Internal "gravity" waves in a plasma layer, Geomagnetism and Aeronomy, (Engl. Transl.), 26, 220–223, 1986.

Sergeev, V. A., Bikkuzina, G. B., and Newell, P. T.: Dayside isotropic precipitation of hot ions, Ann. Geophysicae, 15, 1233–1245, 1997.

Tepley, L. R. and Wentworth, R. C.: Hydromagnetic emission, X-rays, and electron bunches, 1. Experimental results, J. Geophys. Res., 67, 3317–3334, 1962.

Trakhtengerts, V. Y., Demekhov, A. G., Polyakov, S. V., et al.: A mechanism of Pc1 pearl formation based on the Alfvén sweep maser, J. Atmos. Solar-Terr. Phys., 62, 231–238, 2000.

Troitskaya, V. A., Matveeva, E. T., Ivanov, K. G., and Gul'yelmi, A. V.: Change in the frequency of Pc1 micropulsations during a sudden deformation of the magnetosphere, Geomagn. Aeronomy, (Engl. Transl.), 8, 784–786, 1968.

Tsyganenko N. A.: A magnetospheric magnetic field model with a warped tail current sheet. Planet. Space Sci., 37, 5–20, 1989.

Wright, D. M. and Yeoman, T. K.: CUTLASS observations of a high-m ULF wave and its consequences for the DOPE HF Doppler sounder, Ann. Geophysicae, 17, 1493–1497, 1999.